3-D Wave-Structure Interaction with Coastal Sediments - A Multi-Physics/Multi-Solution Techniques Approach

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LONG-TERM GOALS

The long term goal of this proposed research are twofold: (1) develop an advanced multi-physics model with a multi-numerical solution techniques approach to predict nonlinear dynamic behavior of impact burial and flow-induced motion of flexible structures (mines) and surrounding sediments (sand) in the marine environment; and (2) calibrate resulting models with experimental and field measurements. The predictive capability developed in this research will eventually be integrated into an overarching computational framework for the analysis and simulation of the dynamic behavior of naval systems in the marine environment of arbitrary water depth.

OBJECTIVES

The ability to detect and neutralize bottom mines is critically dependent on the scour pattern around the mine and on the degree of the mine burial. The objectives of the first two-years of this research are to first gain an understanding of the structure-fluid-sediment-seabed interaction phenomenon by conducting a literature survey to determine state-of-the-art analytical and numerical modeling capabilities. Then evaluate the current status of analysis and simulation software LS-DYNA in terms of its prediction capabilities for coupled dynamic motions of submerged mines on a seabed in the marine environment and to identify immediately needed developments for further improvement. Simultaneously, survey and examine laboratory and field experiments of the nonlinear dynamic behavior of impact burial and flow-induced motion of mines and scour of surrounding sediments in the marine environment.

APPROACH

The dynamic behavior of submerged mines and their surrounding sediments has been of interest to the Navy in recent years (Inman and Jenkins, 2002). During 1960s-1980s, U.S. Naval scientists developed three burial prediction models that can be used for mine countermeasure tactical planning and for development of environmental support: impact burial, sand ridge migration, and wave-induced scour (Richardson and Briggs 2000). Capabilities for accurate modeling and prediction of motions of mines and their effects on the overall burial behavior at the sea bottom considering the detailed physics of the entire coupled mine-fluid-sediment-seabed "system" is needed. The code LS-DYNA, which is an advanced nonlinear finite-element based commercially available numerical software, has arguably the best solid mechanics, contact and impact models among commercially available software, and has growing fluid mechanic features. It also has an excellent computational framework, and pre- and post-processing capabilities for us to take advantage of in developing additional analysis capabilities to address our research and application needs.

The overall objectives of this research are to be achieved through the following tasks: (1) Conduct a thorough review of literature on mine-fluid-sediment-seabed interaction to determine the state-of-the-art analytical and numerical modeling capabilities; (2) Evaluate the current predictive capability of LS-DYNA for coupled dynamic motions of submerged mines on a seabed in the marine environment; (3) Identify development needs of LS-DYNA for coupled fluid-structure-seabed interaction (mine burial and motion prediction) applications; (4) Plan and implement the immediate needed developments within a two-year timeframe; (5) Examine existing laboratory and field experiments available from ONR on motions of mines on seabed for numerical model calibration; (6) Compare numerical predictions of resulting numerical modules developed with laboratory experiment and field data to validate and calibrate the numerical models for further evaluation; (7) Conduct parametric study of characteristic burial and exposure times, and other parameters as appropriate; and (8) Analyze and document research results and develop a future research plan for further needed modeling improvements.

WORK COMPLETED

In the first two years of this project, we have focused on evaluation of the current status and development of immediately needed capabilities of a multi-physics code LS-DYNA for impact burial and flow-induced motion predictions of mines and its surrounding sediments. While the study of impact burial has been quite active and successful from both analytical and experimental perspectives, the study of motions and scour of buried mines has been restricted mostly to empirical and experimental perspectives. We conducted a review of the literature on impact burial and mine-fluid-sediment-seabed interaction paying special attention to software developed by researches as it is needed to analyze the coupled-FSI interaction problem. We also examined the LS-DYNA software to evaluate its current capabilities from the prospective of modeling the dynamics of the coupled FSI system. There are several soil material models in LS-DYNA, which are currently under investigation, to determine if one of these, if enhanced, would meet the requirement of a cohesionless soil. A brief list of all the soil models in LS-DYNA is given in the appendix. The three common laboratory tests that are performed to get the various material model parameters for the constitutive equations are (i) hydrostatic compression (ii) triaxial compression/extension and (iii) uniaxial strain. The material model parameters that can be calibrated to these data are used in the LS-DYNA soil constitutive models. A selected number of these models were reviewed as possible soil model candidates, from the simplest (material model 5) to the most complex (material model 25). Most of the candidate models in LS-DYNA are extensions of material model 5 (soil and foam). Two of the exceptions to this are model 16 (pseudo-tensor model) and model 25 (geological cap model). Model 5 and its extensions, model 14 (soil and foam with failure), and model 79 (hysteretic soil) are basically an analytical pressure dependent yield surface. Both of these models were indeed found to be unstable in unconfined states. Material model 14 and model 78 (soil and concrete) are for analyses in high-pressure regions. Model 14 was evaluated previously and it was found that it does not simulate low/zero-pressure behavior well. Material model 25 (geological cap model) is a complex model, but does handle low-confinement behavior well. Model 25 cannot simulate strain softening. Despite this shortcoming, it is the only existing model that could simulate much of the basic behavior needed for the present purpose. Because of the cap/shear surface intersection (non-smooth) in model 25, there are many corners in the yield surface. These corners cause the algorithm to be very complex and inefficient. Although there are several other soil material models existing in

LS-DYNA, only those whose material characterization is readily available were investigated. Based on these observations, it was concluded that none of the existing models are ideal for modeling cohesionless sand, and it was decided to test a few of these models for the mine burial tests to determine the capability and needed improvements of LS-DYNA to model cohesionless sand. In order to employ these models for mine-sand interaction simulations, experimental results to determine the material characterization are needed. We assisted in an experiment on scour of sandy seabed around a vertical cylinder and have access to data. We are also in communication with the PI of an on-going field experiment on mine scour being conducted. As a pure continuum approach is not able to capture the complex motion of the sand particles during the settling and burial of mines, we are currently focusing our study on a discrete approach based on the smoothed particle hydrodynamics method for the mine burial problem.

RESULTS

Understanding the burial and re-exposure of submerged/bottom mines placed in nearshore waters, is of paramount interest to the navy. The ability to detect and neutralize bottom mines is critically dependent on the scour pattern around the mine and on the degree of the mine burial. In order to understand the extent to which LS-DYNA can model scour scenario and at the same time comprehend the capability of the software to handle various soil models, a wave generation experiment was conducted to simulate a simple experiment. The model contains the mine, fluid and a piston type wave generator which is defined in rigid shell elements. Geometry and dimension of the wave generating tank was so chosen to generate a 1.20m high wave from the sea level (Sunao Tokura, 2005). The penalty coupling was used to define the fluid-structure interaction. The water was modeled by using solid brick elements. A void domain was created on top of the water domain to capture the wave elevation. The water-void mesh was modeled as a rectangular mesh. The length of the wave generating tank was 40.0m and a width of 6.0m. The height of the water column was 2.0m and size of the void domain was 3.0m. The mine was rectangular in shape (4.0m x 0.8m). The depth of the soil was 1.0m and the mine was allowed to rest on the soil and gravity loading was applied to allow for the mine to settle, before running the wave maker. The numerical wave tank has a non-reflective boundary condition at the far end of the solution domain in order to absorb the wave energy and prevent reflection. The other boundaries of the solution domain are along the side walls of the tank (impermeable no-slip boundary). Figure 1 shows the computational mesh. The tests were repeated for three soil models, however, as the other two tests produced results that are similar in nature, only the results from the first soil model is shown. Fluid density animation plots for the Soil and Foam model at various time steps are shown in Figure 2. The existing models are based on the Drucker-Prager soil models which are directly based on either the Mohr-Coulomb failure surface or the Modified-Mohr–Coulomb failure surface which cannot be used to properly understand the saturated sand behavior. As it is difficult to extrapolate dry sand material properties to those for fully saturated sand, the option of treating saturated sand with the properties of water (low shear strength and high density) was also tested. The simulations thus far utilizes a continuum approach to model each of the fluid, sand, solid mediums using an Arbitrary Lagrangian and Eulerian (ALE) approach. As the use of ALE techniques is not sufficient to fully analyze the scour around the mine, a robust soil model is needed to fully capture the scour scenario. Apart from this an additional material characterization is needed to fully understand the capability of LS-DYNA in handling saturated sand behavior. The key for these kinds of modeling studies is a soil model that includes the pore pressure effects in the saturated sand and clearly none of the existing LS-DYNA geomaterial models include pore pressure into its effect. However, it has been found that a pure continuum approach is not sufficient to capture the complex motion of the sand particles during the settling and burial of mines. A discrete approach such as smooth particle hydrodynamics (SPH), which relies on the equations of state to represent the material behavior, is being investigated as a viable alternative. Retaining a similar wave generation experiment over a sand bed, a comparative study to understand scour scenario around a solid object (mine burial) will be conducted using the SPH method available in LS-DYNA.

SPH is a purely Lagrangian method developed during the 1970's (Lucy 1977; Gingold and Monaghan 1977) in astrophysics to study the collision of galaxies and the impact of bolides on planets. Unlike finite element methods, the SPH method discretizes the deformable object with particles rather than connected meshes. The main advantage, however, arises directly from its Lagrangian nature, since such an approach can tackle difficulties related with lack of symmetry, large voids that may develop in the field, and a free water surface much more efficiently than Eulerian methods can. The SPH technique available in LS-DYNA has been applied for incompressible dynamic fluid flow patterns**.** A series of numerical tests have been carried out to examine the ability and efficiency of SPH formulations in simulating fluid dynamic problems. The SPH method with various formulations can simulate different dynamic fluid flow problems, such as inviscid or viscous flows, compressible or incompressible flows. The SPH option in LS-DYNA was used to simulate the Poiseuille flow and Couette flow. The SPH option in LS-DYNA demands an equation of state and the termination time was set to 0.5 seconds. In the classical hydrodynamics, the flow velocity at a point in the Poiseuille flow or Couette can be obtained by solving the Navier-Stokes momentum equation. In this application the cubic spline function is used. The Poiseuille flow involves flow between two parallel stationary infinite plates placed at $y = 0$ and $y = l$. The initially stationary fluid is driven by a body force F (e.g., pressure difference or external force), gradually flows between the two plates, and finally arrives at a steady state. Couette flow is another often-used benchmark CFD problem. It is a flow between two initially stationary plates placed at $y = 0$ and $y = l$ when the upper plate moves at a certain constant velocity (v_0). The simulations of Poiseuille and Couette flow show that this approach can be furthered to understand the scour around a bottom mine.

IMPACT/APPLICATIONS

The advanced, state-of-the-art FE code LS-DYNA adopted in this project, when fully developed, will enhance the modeling, prediction, operation and control capabilities of the complex mine-fluid-sediment-seabed interaction in general and the numerical simulations of flow-induced mine burial impacts in particular. The 3-D numerical codes being developed will provide additional tools to calibrate and validate the accuracy of the numerical predictions of the modules with laboratory experiment and field data. Figure 3 shows the computational model for coupled fluid-structure interaction (FSI) problem with respect to the mine burial in sand sediments. From the computational sketch it can be seen that the fluid domain followed by the structure and the sand can be modeled using four different computational methods. The fluid domain will be modeled using the fully nonlinear potential flow (FNPF) or the boundary-element method (BEM). Reynolds averaged Navier-Stokes (RANS) and the particle finite element method (PFEM) will be used in the water/mine/sand domain. Sand and the geomaterials around the sand will be modeled using the Smoothed Particle Hydrodynamics method (SPH). The resulting numerical predictive capability will be incorporated into an overarching computational framework for the analysis and simulation of the dynamic behavior of naval systems in the marine environment of arbitrary water depth.

TRANSITIONS

Analysis and simulation capabilities developed in this research can be useful to the various units of the Navy pertinent to mine deployment, detection, burial clearance process studies.

RELATED PROJECTS

The analysis and simulation capabilities developed in this research will be incorporated into a companion project (N00014-07-1-0008) on the development of an overarching computational framework for analysis and prediction of dynamic motions of naval systems in the marine environment in arbitrary water depth.

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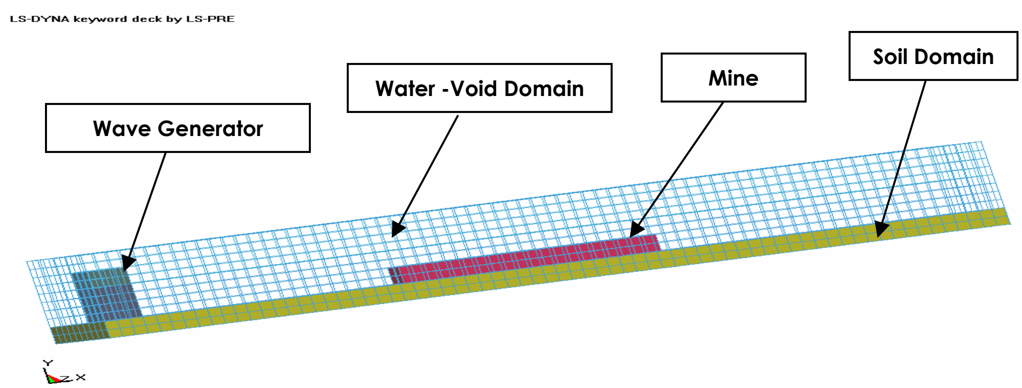

Fig. 1 The computation domain (Isometric View)

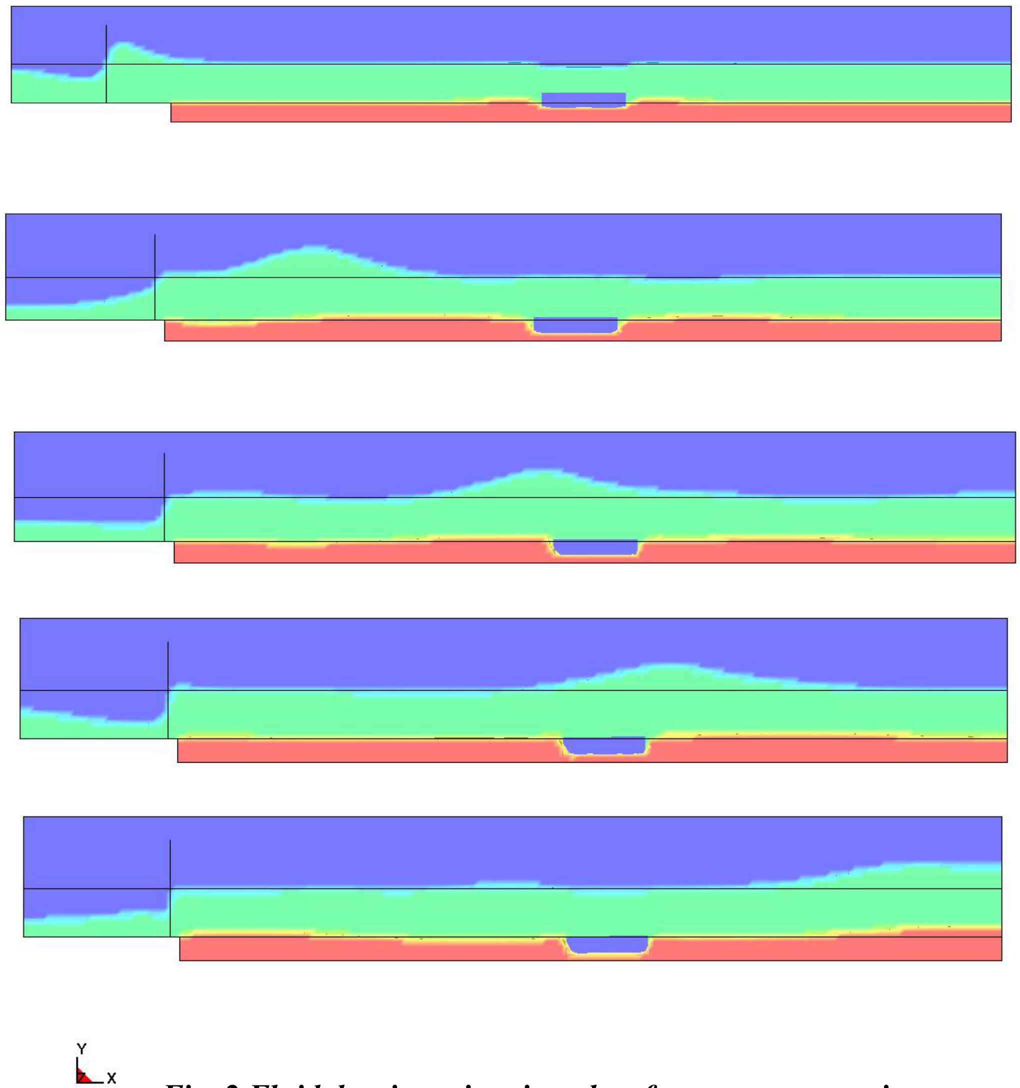

Fig. 2 Fluid density animation plots for wave propagation over a bottom mine at various time steps (Soil and Foam model)

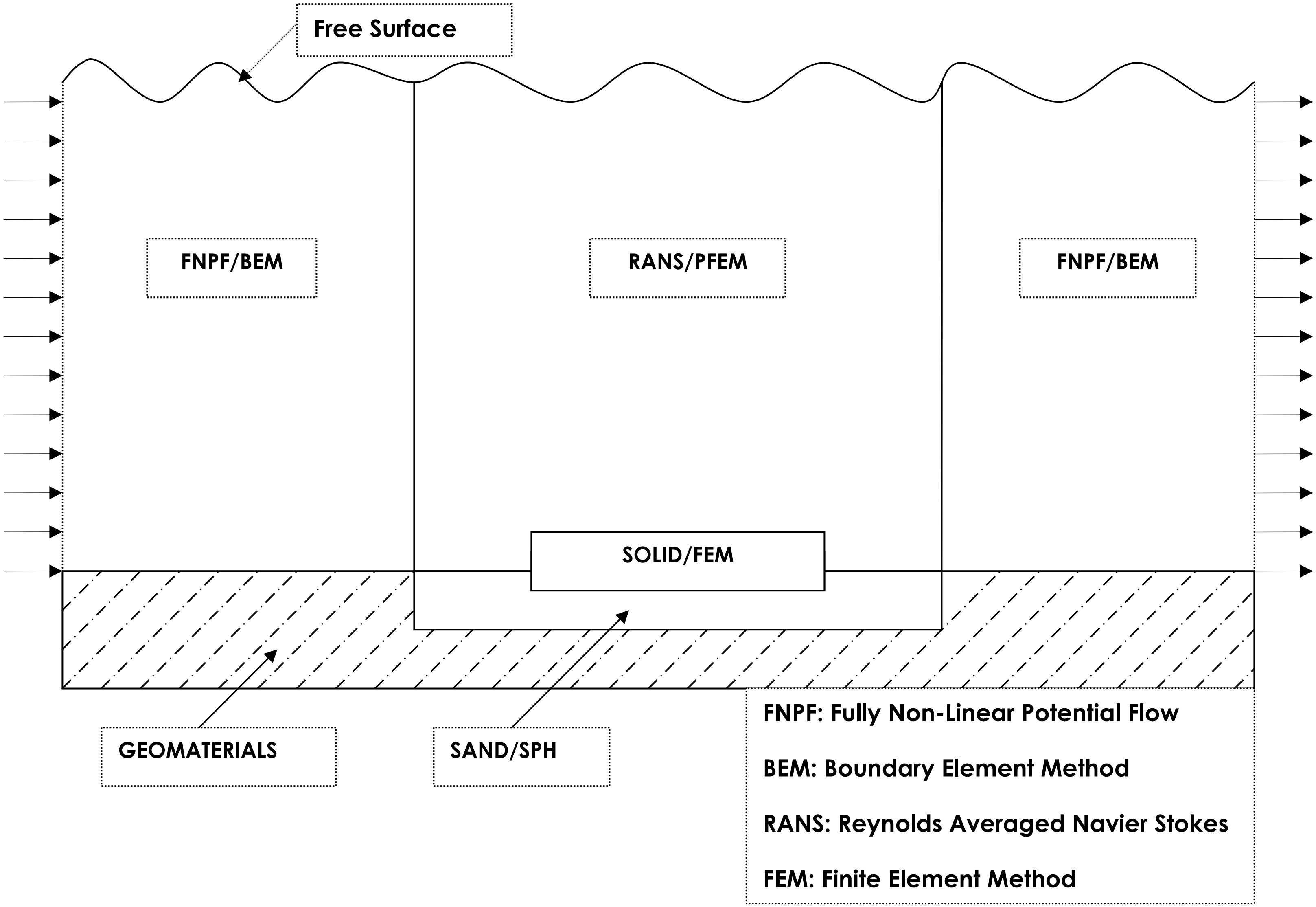

Fig.3 Computation model (various methods that will be used) for the coupled Fluid Structure Interaction (FSI) problem

PUBLICATIONS

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